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(54) Apparatus for emission spectrochemical analysis

Vorrichtung zur spektrochemischen Emissionsanalyse

Dispositif d'analyse spectrochimique d'émission

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- **TECHNICAL DIGEST, no. 35, July 1974, Western Electric; T.H. BRIGGS et al.: "Direct reading laser spectrometer"**
- **ANALYTICAL CHEMISTRY, vol. 52, no. 4, April 1980, pp. 746-753, Ohio, US; D.M. COLEMAN et al.: "High frequency excitation of spark-sampled metal vapor"**

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Description

This invention relates generally to emission spectroscopy and more particularly to an apparatus for emission spectrochemical analysis which utilizes spark discharges or pulses of a laser beam.

There is known a method of emission spectrochemical analysis in which spark discharges or pulses of a laser beam are applied to a sample to be analyzed to cause the sample to emit light, which is analyzed spectroscopically. The method has the following problem: In emission spectrochemical analysis using spark discharge, it is customary to pretreat the surface of a sample to be analyzed by applying spark discharges to the sample surface before analysis is conducted so as to reduce the adverse influence of small scars and/or pinholes on or in the sample surface and/or foreign matters, thereby improving the precision of analysis. For example, for analysis of a sample for 5 seconds the sample must be pretreated with high-energy spark discharges for more than 10 seconds.

The spark discharges for pretreatment of a sample may be referred to as the "preparatory discharges", while the spark discharges for analysis may be referred to as the "analytic discharges".

The reason why the preparatory discharge and the analytic discharge are conducted separately is as follows: Although high-energy discharge has a great capacity for vaporizing a sample, the resulting background light is strong as compared with the spectral line intensity of the component elements of the sample, with resulting decrease in the sensitivity of analysis. Therefore, low-energy discharge is suitable for analysis itself. Thus, after high-energy preparatory discharges have been conducted on a sample for 5 to 10 seconds, several thousand low-energy analytic discharges are conducted to analyze the light from the sample.

If the energy for analytic discharge is too low, however, the amount of the sample components vaporized decreases and the intensity of the light of the spectral emission lines produced becomes weak, with resulting reduction of the sensitivity and precision of analysis. Therefore, a sufficient amount of the sample must be vaporized by analytic discharges, so that there is a limit to which the energy level of the analytic discharges can be lowered, with resulting difficulty in reducing the background light.

As mentioned above, the time required for preparatory discharges is longer than the time required for analytic discharges. The reason why this is so is that the position in the surface of a sample which is struck by each of the spark discharges produced in one operation of analysis is uncertain, so that the whole area of the sample surface must be treated beforehand by preparatory discharges. To improve the precision of analysis a longer period of time is required for preparatory discharge.

Since a sufficient amount of the sample must be vaporized in analytic discharge, the energy for analytic discharge cannot be reduced to a very low level, with resulting difficulty in reducing the background light and obtaining a high sensitivity.

The present inventors have once proposed a method of spectrochemical analysis of a sample containing elements to be analyzed, in which high-energy pulses are cyclically applied onto a small area of a sample to vaporize the components of the sample from the small area thereof, and low-energy spark discharges are generated by a spark generator including an electrode facing the sample so as to be applied to the small area of the sample a predetermined period of time after the application of each high-energy pulse and during the time in which the vaporized components of the sample caused by the application of high energy remains between the sample and the electrode, and the light emitted by - the sample vapor while the low-energy spark discharges are being conducted is spectroscopically measured.

The characteristic of the above-mentioned prior invention is that each and every one of the emissions of light from the sample being analyzed comprises a step of vaporizing the sample and that of analyzing the vaporized elements of the sample. With the method of the prior invention, it is possible to analyze a sample at a cleaned spot on the surface thereof by low-energy spark discharge without pretreatment by conventional preparatory discharge, and to obtain a high sensitivity due to the lowered background level. The circuit arrangement, however, is complicated. In the prior art arrangement the output from the measuring circuit is amplified and sampled by a switching circuit operated synchronously with each emission of light from the sample, and one measuring channel must be provided for each one of the spectral lines of the elements in the sample, and one switching circuit is required for each measuring channel, with resulting complication of the whole circuit arrangement.

Such a prior art method and apparatus for emission spectroscopis analysis is, for example, disclosed in same applicants European Patent EP 0 318 900 A3.

A further prior art arrangement known from the publication "Direct Reading Laser Spectrometer" by T. H. Briggs et. al. in Technical Digest No. 35, July 1974, Western Electric, discloses a laser spectrometer using an array of photomultipliers, one for each spectrum line of interest to be measured, with the photomultipliers each being connected and disconnected to a corresponding evaluating capacitor before and after a laser pulse, respectively, by a switching circuit. Thus, each of the plurality of provided photomultipliers is controlled by a corresponding switching circuit to be connected to the corresponding capacitor.

Accordingly, the primary object of the invention is to simplify the circuit arrangement used in an apparatus for emission spectrochemical analysis which uses a time resolution method of measuring the spectral inten-

sity of light emissions from a sample caused by spark discharge pulses each comprising a high-energy and low-energy portion.

This object is achieved by an apparatus for emission spectrochemical analysis of a sample containing elements to be analyzed according to claim 1.

The photomultiplier tubes are rendered inoperative by cutting off the negative high voltage impressed on the dynodes of the photomultiplier tubes. Since the common negative high-voltage source supplies a voltage to the dynodes of the photomultiplier tubes in the measuring channels, by switching on or off the negative high-voltage source it is possible to control the operation of the photomultiplier tubes in all the measuring channels simultaneously, so that a single switching circuit suffices, with resulting simplification of the circuit arrangement of the apparatus.

Fig. 1 is a block diagram schematically showing one embodiment of the invention;

Fig. 2 is an electrical circuit diagram of a portion of Fig. 1;

Fig. 3 is a waveform diagram for explaining the operation of the apparatus of the invention;

Fig. 4 is a block diagram schematically showing another embodiment of the invention; and

Fig. 5 is a block diagram schematically showing a third embodiment of the invention.

Fig. 1 schematically shows one embodiment of the invention, which comprises a spark generator 10, an ignitor 11, a spectrometer 12, a photosensor PS and a readout circuit 13. A sample 14 to be analyzed and an electrode 15 are juxtaposed across an analytical gap g, with the ignitor 11 being connected thereto through a trigger spark gap g'.

The photosensor PS comprises a plurality of photomultiplier tubes P_1, P_2, ··· P_n arranged at predetermined wavelength positions on the spectral plane of the spectrometer 12. A negative high-voltage source 16 is connected to the dynodes of the photomultiplier tubes P_1, P_2, ··· P_n through sensitivity attenuators R_1, R_2, ··· R_n, respectively. The readout circuit 13 comprises a plurality of capacitors C_1, C_2, ··· C_n and a multiplexer 20. The outputs of the photomultiplier tubes P_1, P_2, ··· P_n are stored in the capacitors C_1, C_2, ··· C_n, respectively, the outputs of which are applied to a computer CPU through the multiplexer 20 and an analog/digital converter A/D.

A photodetector 17 is provided adjacent the trigger spark gap g' to detect the light caused by a trigger discharge and produce a detection pulse, which is applied to a timing circuit 18 which comprises a series combination of two one-shot circuits. The timing circuit 18 produces one output pulse having a certain width a certain period of time after the detection pulse from the photodetector 17 is applied thereto. The output pulse from the timing circuit 18 renders conducting a switching circuit 19 connected between the negative high-voltage source 16 and the ground.

The instant a spark is generated in the trigger spark gap g', , a spark discharge is triggered in the analytical gap g of the spark generator 10. Therefore, by detecting the light caused to emit by a spark in the trigger spark gap g' and rendering the switching circuit 19 conducting for a predetermined period of time after a certain period of time, it is possible to sample the output from the photomultiplier tubes P_1, P_2 . . . P_n for a predetermined period of time during the discharge in the analytical gap.

Fig. 2 schematically shows an example of the spark generator 10, which comprises capacitors K_1 and K_2 for storing energy to be discharged, inductors L_1 and L_2 with a protective diode D_1, D_2 connected across each of the capacitors, and a direct current source 21 which charges the capacitors. The capacitor K_1 is connected to the analytical gap g through the inductor L_1 , and the capacitor K_2 is connected to the analytical gap g through the series combination of inductors L_1 and L_2. The ignitor 11 is connected across the analytical gap g through the trigger spark gap g'.

When a discharge is generated in the trigger spark gap g' by a trigger pulse produced by the ignitor 11, the discharge current breaks the insulation of the analytical gap g and passes therethrough, whereupon the electric charge stored in the capacitors K_1 and K_2 is discharged through the analytical gap g. Since the electric charge of the capacitor K_2 is discharged through the inductors L_1 and L_2 connected in series, the discharge is conducted slowly. On the other hand, since the electric charge of the capacitor K_1 is discharged through the inductor L_1 only, the discharge is conducted quickly. In other words, the charge of the capacitor K_1 is discharged first and then the charge of the capacitor K_2 is discharged. With the capacitor K_1 of a larger capacity than that of the capacitor K_2, it is possible to supply a larger amount of energy from the first capacitor K_1 and a smaller amount of energy from the second capacitor K_2.

Fig. 3 shows a waveform of a spark discharge generated in the analytical gap g. As shown in the figure each of the spark discharges generated in the analytical gap for one operation of analysis of a sample comprises a high-energy portion e_1 and a low-energy portion e_2 continuing from the high-energy portion. The timing circuit 18 receives the detection pulse when the photodetector 17 detects a trigger spark discharge e_t at t_1 and after a period of time corresponding to the high-energy portion e_1 of the spark discharge in the analytical gap, the timing circuit 18 produces an output pulse a at t_2 to close the switching circuit 19 thereby to cause the negative high-voltage source 16 to activate the photomultiplier tubes $P_1 \sim P_n$, which detect the corresponding emission lines in the spectrum of the sample caused by the low-energy portion e_2 of the spark discharge and produce corresponding electrical signals.

In the above embodiment a negative high voltage is impressed on the dynodes of the photomultiplier tubes

only during the low-energy excitation of the sample. It is also possible to prevent impression of a negative high voltage on the dynodes only during the high-energy excitation of the sample.

Fig. 4 shows another embodiment of the invention, wherein a laser is used for vaporization of the sample. In Fig. 4 the same reference numerals as in Fig. 1 designate corresponding elements in Fig. 1, so that no explanation will be given to them except when necessary. The apparatus comprises a laser source 30, a circuit 31 for driving the source 30 to produce pulses of high-energy laser beam at a predetermined cycle, and a lense 32 for focusing the laser beam onto a point on the surface of a sample 14 thereby to cause the material of the sample at the point to vaporize. At one side of the laser beam there is provided a beam detector 17 which detects each pulse of the laser beam to produce a detection signal, which triggers the timing circuit 18. Upon passage of a time preset in the timing circuit, the circuit produces an output signal to cause the spark generator 10 to produce a low-energy spark discharge in the analytical gap g between the sample 14 and the electrode 15. The output from the timing circuit 18 is also applied to the switching circuit 19 to close the circuit thereby to cause the negative high-voltage source 16 to activate the photomultiplier tubes $P_1 \sim P_n$ to operate in the same manner as described with reference to Fig. 1.

Fig. 5 shows a third embodiment of the invention wherein a laser is used for both high-energy and low-energy excitation of the sample. To this end, the driving circuit 31 in Fig. 5 is so designed as to cause the laser source 30 to produce laser pulses each having a high-energy portion and a low-energy portion such as shown in Fig. 3. Upon passage of a period of time corresponding to the high-energy excitation after the photodetector 17 detects the high-energy portion of each laser pulse, the timing circuit 18 produces an output pulse to close the switching circuit 19, whereupon the negative high-voltage source impresses a negative high voltage on the dynodes of the photomultiplier tubes $P_1 \sim P_n$ for activation thereof. In Fig. 5 the same reference numerals as in Fig. 1 or 4 designate corresponding elements in Fig. 1 or 4, and the readout circuit 13 operates in substantially the same manner as in the previous embodiments.

In accordance with the invention, it is possible to simplify the circuit arrangement for emission spectrochemical analysis of a sample wherein each of a number of emissions of light from the sample for one operation of analysis is caused by both high-energy and low-energy excitation of the sample, and no preparatory discharge need be conducted on the sample. Since high-energy excitation is immediately followed by low-energy excitation, it is possible with a smaller amount of energy than otherwise to cause the sample vapor to emit light, with resulting reduction of the background noise, improvement of the sensitivitv and precision of analysis, and reduction of the manfacturing cost of the apparatus.

Claims

1. An apparatus for emission spectrochemical analysis of a sample (14) containing elements to be analyzed, comprising:

exciting means (10, 11) for cyclically exciting said sample with relatively high energy to vaporize said elements contained in said sample (14) and successively with relatively low energy to cause said vaporized elements to emit light;
light measuring means (12, 13, PS) for measuring the light emitted by said vaporized elements; and
detection means (17) for detecting each cycle of said exciting means (10, 11) and producing a detection pulse in response thereto;

characterized in that
said light measuring means comprises:

spectrometer means (12) for dispersing the light emitted by said vaporized elements to produce a spectrum containing spectral lines characteristic of said elements; and
a plurality of photomultiplier tubes (P1, ..., Pn) having a corresponding plurality of dynodes, with each of said photomultiplier tubes being so arranged as to receive the light of one of said spectral lines to produce a corresponding electric signal; and

a single negative high-voltage source (16) connected to said dynodes is provided; and
said detection pulse is supplied to a control means (18, 19) for controlling said negative high-voltage source (16) to impress a negative high voltage upon said dynodes of said photomultiplier tubes during said low-energy excitation of said sample (14), so that said photomultiplier tubes receive said light of said spectral lines to produce a corresponding electrical signal, while preventing said negative high voltage from being impressed upon said dynodes during said high-energy excitation of said sample (14);
said control means comprising a timing circuit (18) for receiving said detection pulse and for producing an output pulse supplied to a single switching circuit (19) and causing said single switching circuit (19) in response to said output pulse to control said photomultiplier tubes (P1, ..., Pn); said single switching circuit (19) being connected between said negative high-voltage source (16) and ground.

2. An apparatus according to claim 1,
characterized in that
said exciting means (10, 11) comprises means for producing spark discharges each having a wave-

form which comprises a relatively high-energy portion and a relatively low-energy portion continuing from said high-energy portion.

3. An apparatus according to claim 1,
characterized in that
said exciting means (10, 30, 31) comprises a laser (30) for producing a laser beam to be applied to said sample (14) to vaporize said elements contained therein and a spark generator (10) to generate a spark to cause said vaporized elements to emit light.

4. An apparatus according to claim 1,
characterized in that
said exciting means (30, 31) comprises a laser (30) for producing a laser beam of high energy to be applied to said sample (14) to vaporize said elements contained therein and a laser beam of low energy to be applied to said vaporized elements to cause emission of light therefrom.

5. An apparatus according to claim 1,
characterized in that
said single switching means (19) is a normally open switching circuit which, in response to said timing circuit (18) is closed during said low-energy excitation of said sample (14) to thereby cause said negative high-voltage source to activate said photomultiplier tubes (P1, ..., Pn).

6. An apparatus according to claim 1,
characterized in that
said single switching means (19) is a normally closed switching circuit which, in response to said timing circuit (18) is opened during said high-energy excitation of said sample (14) to thereby prevent said negative high-voltage source to activate said photomultiplier tubes (P1, ..., Pn).

Patentansprüche

1. Vorrichtung zur spektrochemischen Emissionsanalyse einer zu analysierende Elemente enthaltenden Probe (14) mit

einer Anregungseinrichtung (10, 11) zur zyklischen Anregung der Probe mit relativ hoher Energie zur Verdampfung der in der Probe (14) enthaltenen Elemente und nachfolgend mit relativ niedriger Energie, um die verdampften Elemente zur Emission von Licht zu veranlassen,
einer Lichtmeßeinrichtung (12, 13, PS) zur Messung des von den verdampften Elementen emittierten Lichts und
einer Erfassungseinrichtung (17) zur Erfassung jedes Zyklus der Anregungseinrichtung (10, 11) und zur Erzeugung eines Erfassungsimpulses im Ansprechen darauf,

dadurch gekennzeichnet, daß

die Lichtmeßeinrichtung

eine Spektrometereinrichtung (12) zur Dispersion des von den verdampften Elementen emittierten Lichts zur Erzeugung eines die für die Elemente charakteristischen Spektrallinien enthaltenden Spektrums und
eine Vielzahl von Photovervielfacherröhren (P1, ..., Pn) mit einer entsprechenden Vielzahl von Dynoden enthält, wobei jede der Photovervielfacherröhren derart angeordnet ist, daß sie das Licht einer der Spektrallinien empfängt, um ein entsprechendes elektrisches Signal zu erzeugen und

eine einzelne an die Dynoden angeschlossene negative Hochspannungsquelle (16) vorgesehen ist und
der Erfassungsimpuls einer Steuereinrichtung (18, 19) zur Steuerung der negativen Hochspannungsquelle (16) zugeführt wird, um eine negative Hochspannung an die Dynoden der Photovervielfacherröhren während der Anregung der Probe (14) mit niedriger Energie anzulegen, so daß die Photovervielfacherröhren das Licht der Spektrallinien zur Erzeugung eines entsprechenden elektrischen Signals empfangen, während das Anlegen der negativen Hochspannung an die Dynoden während der Anregung der Probe (14) mit hoher Energie verhindert wird,
wobei die Steuereinrichtung eine Zeitsteuerschaltung (18) zum Empfang des Erfassungsimpulses und zur Erzeugung eines einem einzelnen Schalterschaltkreis (19) zugeführten Ausgangsimpulses enthält und den einzelnen Schalterschaltkreis (19) im Ansprechen auf den Ausgangsimpuls zur Steuerung der Photovervielfacherröhren (P1, ..., Pn) veranlaßt,
wobei der einzelne Schalterschaltkreis (19) zwischen der negativen Hochspannungsquelle (16) und Masse angeschlossen ist.

2. Vorrichtung nach Anspruch 1,
dadurch gekennzeichnet, daß
die Anregungseinrichtung (10, 11) eine Einrichtung zur Erzeugung von Funkenentladungen mit jeweils einem Signalverlauf enthält, der einen Abschnitt relativ hoher Energie und einen Abschnitt relativ niedriger Energie im Anschluß an den Abschnitt hoher Energie enthält.

3. Vorrichtung nach Anspruch 1,
dadurch gekennzeichnet, daß
die Anregungseinrichtung (10, 30, 31) einen Laser (30) zur Erzeugung eines zur Verdampfung der in der Probe enthaltenen Elemente auf die Probe (14) zu richtenden Laserstrahls und einen Funkengenerator (10) zur Erzeugung eines die verdampften Elemente zur Emission von Licht veranlassenden Funkens enthält.

4. Vorrichtung nach Anspruch 1,
dadurch gekennzeichnet, daß
die Anregungseinrichtung (30, 31) einen Laser (30) zur Erzeugung eines zur Verdampfung der in der Probe enthaltenen Elemente auf die Probe (14) zu richtenden Laserstrahls hoher Energie und eines zur Lichtemission der verdampften Elemente auf die verdampften Elemente zu richtenden Laserstrahls von niedriger Energie enthält.

5. Vorrichtung nach Anspruch 1,
dadurch gekennzeichnet, daß
die einzelne Schalteinrichtung (19) im Grundzustand ein geöffneter Schalterschaltkreis ist, der im Ansprechen auf die Zeitsteuerschaltung (18) während der Anregung der Probe (14) mit niedriger Energie geschlossen wird, um dadurch Photovervielfacherröhren (P1, ..., Pn) durch die negative Hochspannungsquelle zur aktivieren.

6. Vorrichtung nach Anspruch 1,
dadurch gekennzeichnet, daß
die einzelne Schalteinrichtung (19) im Grundzustand ein geschlossener Schalterschaltkreis ist, der im Ansprechen auf die Zeitsteuerschaltung (18) während der Anregung der Probe (14) mit hoher Energie geöffnet wird, um dadurch die Aktivierung der Photovervielfacherröhren (P1, ..., Pn) durch die negative Hochspannungsquelle zu verhindern.

Revendications

1. Dispositif pour l'analyse spectrochimique d'émission d'un échantillon (14) contenant des éléments devant être analysés, comprenant :

des moyens d'excitation (10, 11) pour exciter de façon cyclique ledit échantillon avec une énergie relativement élevée afin de vaporiser lesdits éléments contenus dans ledit échantillon (14), et ensuite avec une énergie relativement faible afin de provoquer l'émission de lumière par lesdits éléments vaporisés ;
des moyens de mesure de lumière (12, 13, PS) pour mesurer la lumière émise par lesdits éléments vaporisés ; et
des moyens de détection (17) pour détecter chaque cycle desdits moyens d'excitation (10, 11) et produire une impulsion de détection en réponse à ceux-ci ;

caractérisé en ce que :
lesdits moyens de mesure de lumière comprennent :

des moyens formant spectromètre (12) pour disperser la lumière émise par lesdits éléments vaporisés afin de produire un spectre contenant des lignes spectrales caractéristiques desdits éléments ; et
une pluralité de tubes photomultiplicateurs (P1, ..., Pn) comportant une pluralité correspondante de dynodes, chacun desdits tubes photomultiplicateurs étant configuré de façon à recevoir la lumière de l'une desdites lignes spectrales afin de produire un signal électrique correspondant ; et
une source de haute tension négative unique (16) connectée auxdites dynodes est présente ; et
ladite impulsion de détection est délivrée à des moyens de commande (18, 19) pour commander ladite source de haute tension négative (16) afin de communiquer une haute tension négative auxdites dynodes desdits tubes photomultiplicateurs durant ladite excitation à faible énergie dudit échantillon (14), de telle sorte que lesdits tubes photomultiplicateurs reçoivent ladite lumière desdites lignes spectrales afin de produire un signal électrique correspondant, tout en empêchant ladite haute tension négative d'être appliquée auxdites dynodes durant ladite excitation à énergie élevée dudit échantillon (14) ;
lesdits moyens de commande comprenant un circuit de minutage (18) pour recevoir ladite impulsion de détection et pour produire une impulsion de sortie délivrée à un circuit de commutation unique (19) et pour faire commander par ledit circuit de commutation unique (19), en réponse à ladite impulsion de sortie, lesdits tubes photomultiplicateurs (P1, ..., Pn) ;
ledit circuit de commutation unique (19) étant connecté entre ladite source de haute tension négative (16) et la masse.

2. Dispositif selon la revendication 1, caractérisé en ce que :
lesdits moyens d'excitation (10, 11) comprennent des moyens pour produire des décharges d'étincelle ayant chacune une forme d'onde qui comprend une partie à énergie relativement élevée et une partie à énergie relativement faible à la suite de ladite partie à énergie élevée.

3. Dispositif selon la revendication 1, caractérisé en ce que :

lesdits moyens d'excitation (10, 30, 31) comprennent un laser (30) pour produire un faisceau laser devant être appliqué audit échantillon (14) afin de vaporiser lesdits éléments contenus à l'intérieur de celui-ci et un générateur d'étincelles (10) pour générer une étincelle afin de provoquer l'émission de lumière par lesdits éléments vaporisés.

4. Dispositif selon la revendication 1, caractérisé en ce que :

lesdits moyens d'excitation (30, 31) comprennent un laser (30) pour produire un faisceau laser d'énergie élevée devant être appliqué audit échantillon (14) afin de vaporiser lesdits éléments contenus à l'intérieur de celui-ci et un faisceau laser de faible énergie devant être appliqué auxdits éléments vaporisés afin de provoquer l'émission de lumière à partir de ceux-ci.

5. Dispositif selon la revendication 1, caractérisé en ce que :

lesdits moyens de commutation uniques (19) sont un circuit de commutation normalement ouvert, qui, en réponse audit circuit de minutage (18) est fermé durant ladite excitation à faible énergie dudit échantillon (14) afin de provoquer par conséquent l'activation par ladite source à haute tension négative desdits tubes photomultiplicateurs (P1, ..., Pn).

6. Dispositif selon la revendication 1, caractérisé en ce que :

lesdits moyens de commutation uniques (19) sont un circuit de commutation normalement fermé, qui, en réponse audit circuit de minutage (18) est ouvert durant ladite excitation à énergie élevée dudit échantillon (14) afin d'empêcher par conséquent ladite source de haute tension négative d'activer lesdits tubes photomultiplicateurs (P1, ..., Pn).

Fig. 1

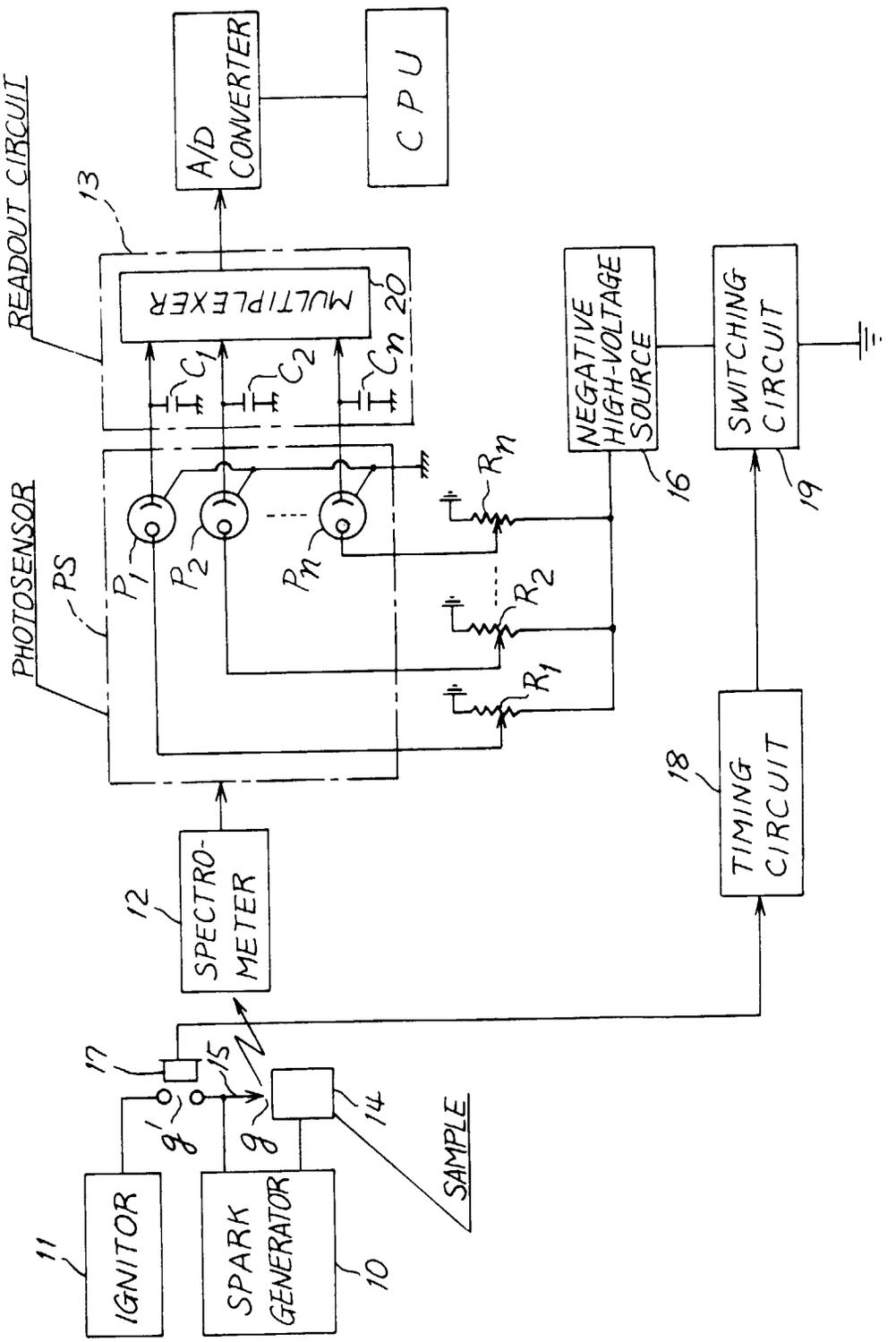

READOUT CIRCUIT
13
A/D CONVERTER
CPU
MULTIPLEXER
20
C1
C2
Cn
PHOTOSENSOR
PS
P1
P2
Pn
Rn
R2
R1
NEGATIVE HIGH-VOLTAGE SOURCE
16
SWITCHING CIRCUIT
19
12
SPECTRO-METER
18
TIMING CIRCUIT
17
15
g'
g
14
SAMPLE
11
IGNITOR
SPARK GENERATOR
10

Fig. 2

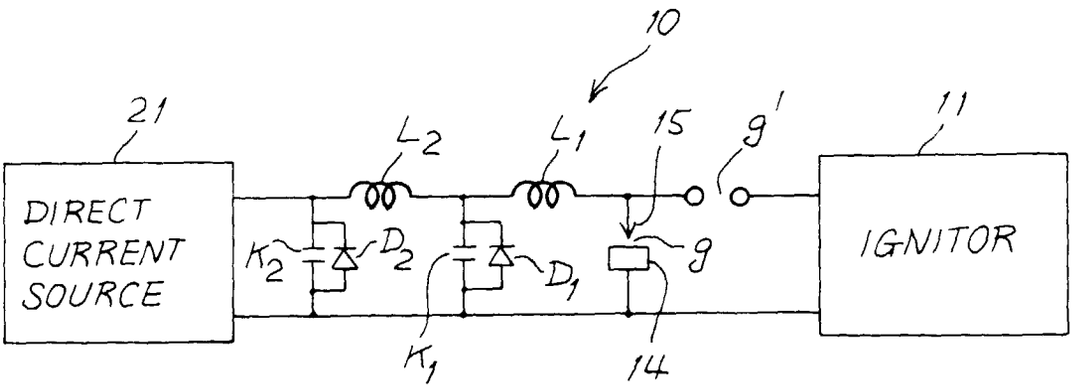
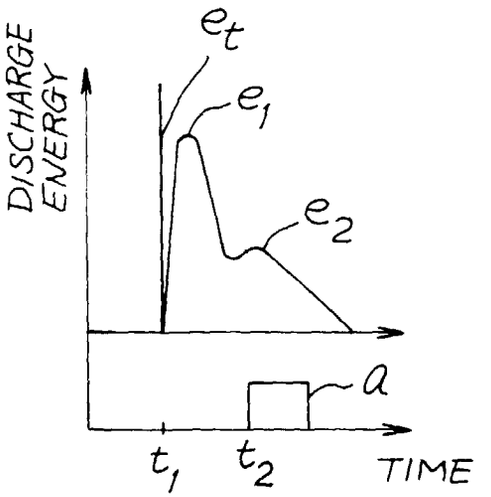

10
21
L_2
L_1
15
g'
11
DIRECT CURRENT SOURCE
K_2
D_2
D_1
g
IGNITOR
K_1
14

Fig. 3


DISCHARGE ENERGY
e_t
e_1
e_2
a
t_1
t_2
TIME

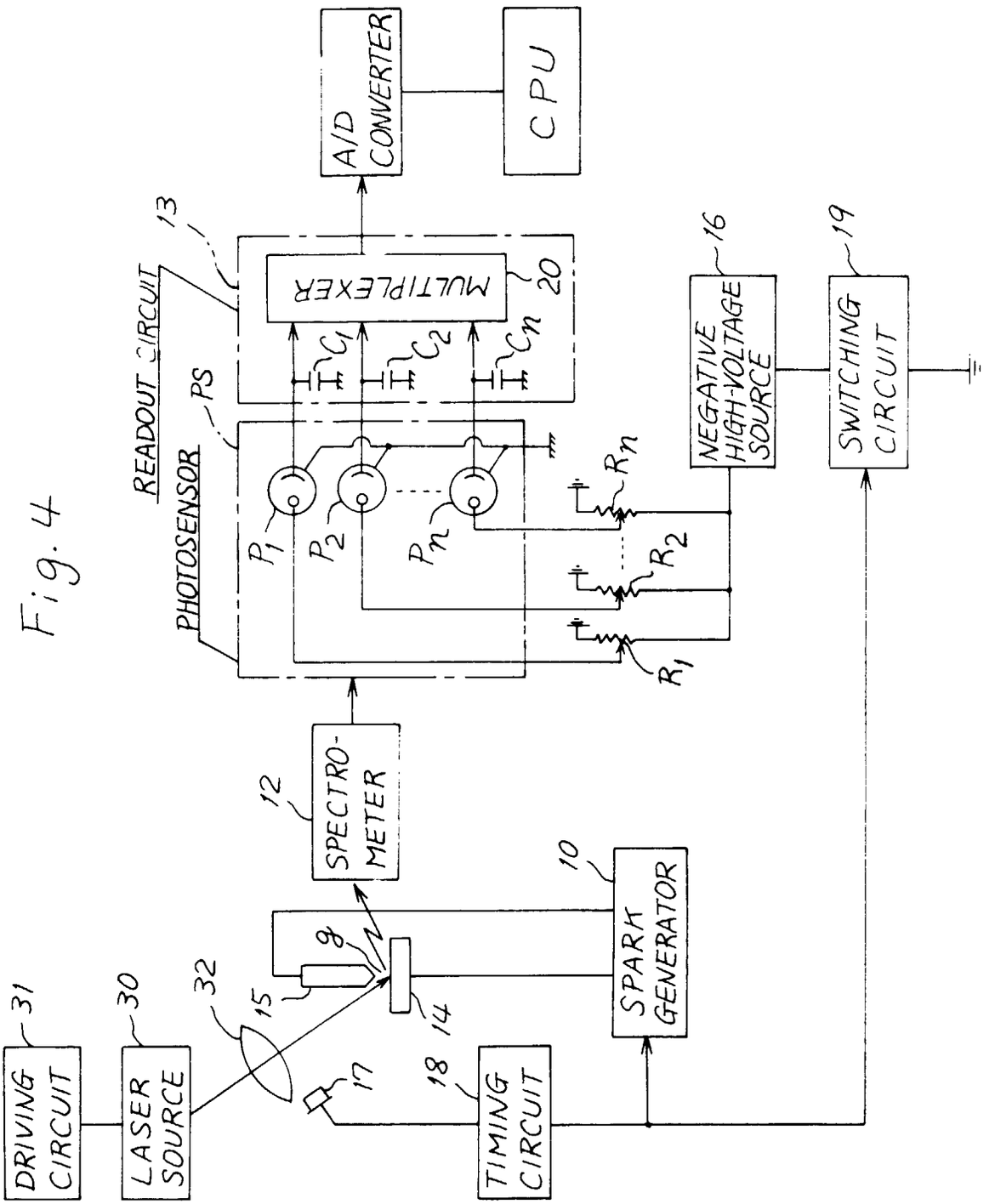

DRIVING CIRCUIT
31
LASER SOURCE
30
32
15
17
18
TIMING CIRCUIT
14
9
SPARK GENERATOR
10
SPECTRO-METER
12
READOUT CIRCUIT
13
PHOTOSENSOR
PS
P1
P2
Pn
C1
C2
Cn
MULTIPLEXER
20
A/D CONVERTER
CPU
R1
R2
Rn
NEGATIVE HIGH-VOLTAGE SOURCE
16
SWITCHING CIRCUIT
19

Fig. 4

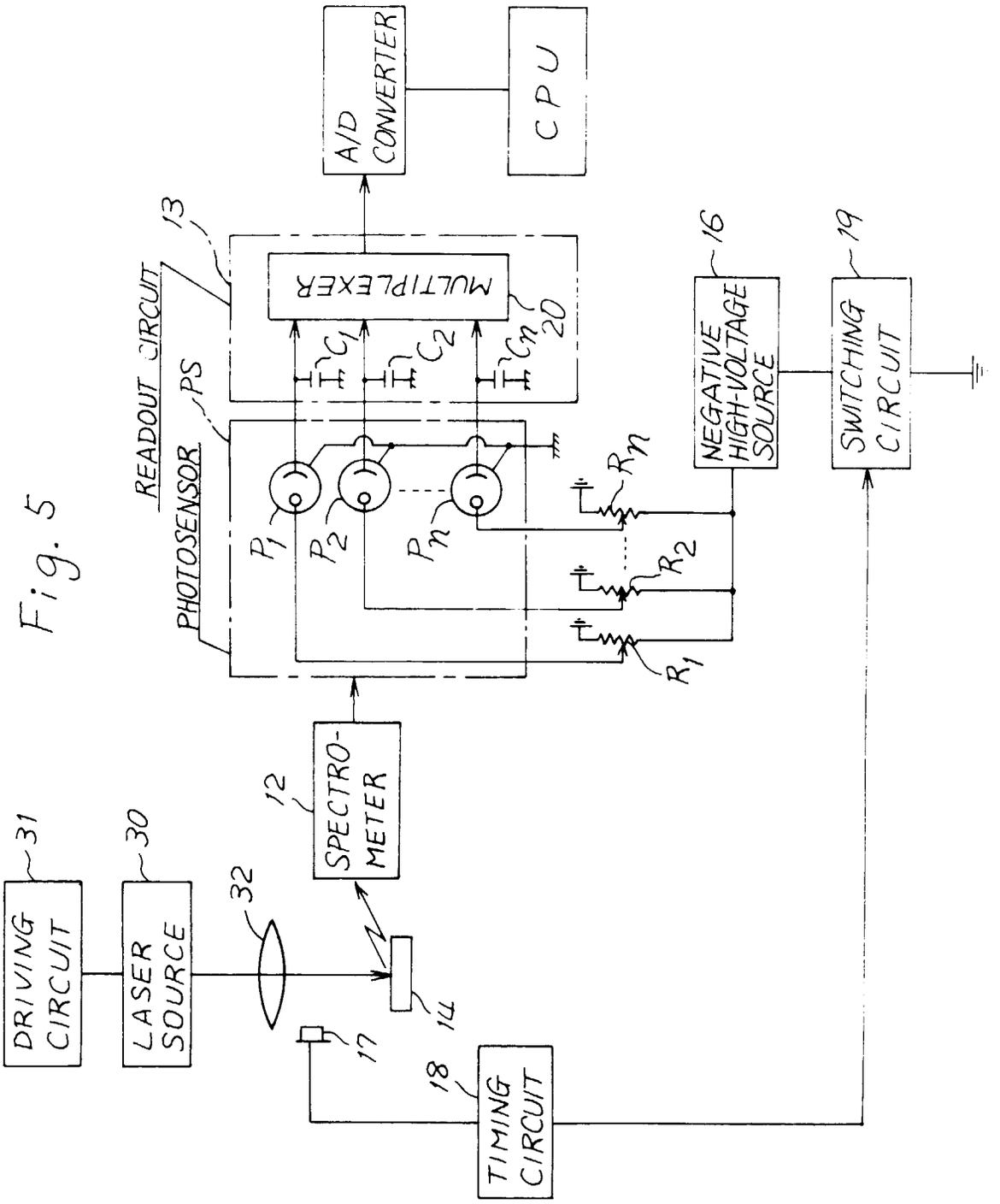

DRIVING CIRCUIT
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Fig. 5